

Failure Analysis of Transverse Cracks in API 5L X70M Pipes

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How to cite this paper: Kumar, A., Sharma, K., Yadav, V., Banerjee, D.K. and Marvel, R. (2025) Failure Analysis of Transverse Cracks in API 5L X70M Pipes. *Open Journal of Applied Sciences*, 15, 1214-1224.
<https://doi.org/10.4236/ojapps.2025.155084>

Received: April 1, 2025

Accepted: May 16, 2025

Published: May 19, 2025

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Abstract

This study explores the critical failure mechanisms in API 5L X70M pipeline steel, focusing on the development of transverse cracks that compromise pipeline integrity. API 5L X70M, widely used in high-pressure oil and gas pipelines, is favored for its high strength and toughness. However, transverse cracking poses a serious risk to the safe operation of pipelines, potentially leading to catastrophic failures. Understanding the origin and propagation of these cracks is essential for ensuring the reliability and longevity of pipelines in challenging environments. In this investigation, a comprehensive failure analysis was conducted using non-destructive testing (NDT), metallographic examination, mechanical property assessment, and fracture surface analysis via scanning electron microscopy (SEM). The findings indicate that transverse cracks initiate due to residual stresses from the manufacturing process, environmental influences, and cyclic loading conditions. Microstructural defects, including inclusions and weakened grain boundaries, were identified as key sites for crack initiation. Additionally, mechanisms such as hydrogen-induced cracking (HIC) and stress corrosion cracking (SCC) were found to contribute to crack propagation. Additionally, mechanisms such as hydrogen-induced cracking (HIC) and stress corrosion cracking (SCC) were observed to contribute to crack propagation in specific environmental conditions, as evidenced by SEM and EDS analyses showing hydrogen-related embrittlement and corrosion products, though their precise roles require further investigation. This study underscores the importance of early detection and mitigation strategies, including enhanced manufacturing controls and operational monitoring, to prevent transverse crack formation and ensure pipeline safety in critical applications.

Keywords

API (American Petroleum Institute), SAW, Transverse Crack, Microstructural Defects, Ultrasonic Testing, Radiography, EDS, SEM

1. Introduction

1.1. Applications of API 5L X70M Pipes

- 1) **Oil and Gas Transportation:** Transporting crude oil, natural gas, and refined products over long distances.
- 2) **Pipeline Construction:** Mainline transmission pipelines and distribution networks.
- 3) **Subsea Pipelines:** Used in offshore and underwater applications due to their high-strength properties.
- 4) **High-Pressure Systems:** Ideal for environments requiring durability under high stress and pressure.
- 5) **Structural Applications:** Sometimes used in heavy-duty structural frameworks.

This study focuses on a select number of API 5L X70M pipe samples, tested in accordance with API 5L 46th edition, to investigate transverse crack formation under specific operational and environmental conditions. While the findings provide valuable insights into crack initiation and propagation mechanisms, their generalizability to other X70M pipelines operating under different conditions (e.g., varying soil compositions, pressure regimes, or corrosive environments) may be limited. Further studies with broader sample sets and diverse conditions are recommended to validate and extend these results [1].

1.2. Importance of Failure Analysis

Failures in pipelines can have significant impacts across safety, environmental, and economic domains [2]:

- 1) **Safety:** Pipeline failures can cause explosions, fires, or toxic leaks, endangering lives and property. Communities near pipelines face risks of injury, fatalities, and displacement in case of catastrophic failures.
- 2) **Environmental Concerns:** Spills or leaks release hazardous substances into the soil, water, and air, leading to long-term ecological damage. They harm wildlife, contaminate water supplies, and degrade ecosystems, with cleanup often requiring extensive time and resources.
- 3) **Economic Implications:** Pipeline failures result in substantial financial losses due to repair costs, legal liabilities, regulatory fines, and environmental remediation. Disruption in energy or material supply chains can also lead to broader economic impacts, such as increased fuel prices and lost revenue for businesses.
- 4) Preventive maintenance, rigorous inspections, and robust response mechanisms are critical to mitigating these risks [3].

1.3. Objective of the Study

The causes of transverse cracks in pipes typically include:

- 1) **Material Defects:** Poor-quality materials or manufacturing defects, such as inclusions, voids, or improper heat treatment [4].
- 2) **Thermal Stress:** Uneven cooling or heating causing expansion or contraction beyond material limits [5].
- 3) **Mechanical Stress:** Overloading, impact forces, or excessive pressure during operation or installation [6].
- 4) **Corrosion:** Localized weakening due to chemical reactions or environmental factors [7].
- 5) **Fatigue:** Repeated cyclic stresses over time, leading to crack initiation and growth [8].
- 6) **Welding Issues:** Improper welding techniques or residual stresses from welding.
- 7) **Design Flaws:** Poor design, sharp corners, or inadequate wall thickness.
- 8) **Soil or Ground Movement:** Uneven support or shifting of the ground around buried pipes.

Transverse cracks can significantly impact the structural integrity [9], performance, and safety of pipes under various conditions:

- 1) **Structural Integrity:** Transverse cracks weaken the pipe by creating stress concentration points, making it more susceptible to failure under internal pressure or external loads. The severity depends on crack size, depth, and location, with larger or deeper cracks posing greater risks.
- 2) **Performance:** Cracks can lead to leaks, reducing the pipe's efficiency in transporting fluids or gases. They may accelerate corrosion or degradation by exposing the material to environmental factors. Cracks can propagate under cyclic loading, compromising long-term performance.
- 3) **Safety:** Pipes with transverse cracks are at a higher risk of catastrophic failure, especially in high-pressure or high-temperature conditions. Cracks in pipes carrying hazardous materials (e.g., chemicals or gas) can lead to environmental and health hazards.

1.4. Influencing Conditions

- 1) **Internal Pressure:** Higher pressures exacerbate crack growth and increase the likelihood of rupture.
- 2) **Temperature Variations:** Thermal stresses from temperature fluctuations can accelerate crack propagation.
- 3) **Loading Cycles:** Repeated mechanical stresses (e.g., vibrations or dynamic loads) promote fatigue crack growth.
- 4) **Corrosive Environments:** Corrosion can amplify the effects of cracks by eroding the pipe material around the defect.

To prevent or minimize transverse cracks, consider the following recommendations:

1.5. Improved Design

- 1) **Proper Joint Spacing:** Design appropriate joint spacing to accommodate thermal expansion and contraction.
- 2) **Adequate Reinforcement:** Use reinforcing steel or fibers to control crack widths and spacing.
- 3) **Base Support:** Ensure uniform and stable subgrade to prevent uneven stress distribution.

1.6. Maintenance Practices

- 1) **Sealing Joints and Cracks:** Apply sealants to prevent water infiltration and freeze-thaw cycles.
- 2) **Timely Repairs:** Address small cracks early to prevent propagation.
- 3) **Surface Treatments:** Use overlays or surface rejuvenators to extend pavement life and protect against thermal stress.

2. Literature Review

Previous studies on pipeline failures have highlighted transverse cracks as critical defects that compromise structural integrity. These cracks typically occur perpendicular to the pipeline's axis and are often caused by factors such as mechanical stress, fatigue, corrosion, or welding defects. Research indicates that environmental conditions, such as temperature fluctuations and soil movement, can exacerbate the propagation of transverse cracks [10]. Advanced inspection techniques like ultrasonic testing, magnetic flux leakage, and acoustic emission monitoring have been employed to detect and assess these cracks. Studies emphasize the importance of material selection, welding quality, and regular maintenance to mitigate such failures [9].

Summary of Findings

- **Material Properties**

- 1) Mechanical, thermal, and chemical properties significantly influence performance.
- 2) Variations in composition or microstructure can affect strength, durability, and fatigue resistance.

- **Manufacturing Defects**

- 1) Defects like porosity, cracks, and inclusions can weaken structural integrity.
- 2) Poor quality control can lead to reduced lifespan or failure under load.

- **Environmental Effects**

- 1) Factors such as temperature, humidity, corrosion, and UV exposure degrade materials over time.
- 2) Environmental compatibility is critical for material selection in extreme conditions.

- **Stress Factors**

- 1) Repeated or excessive loads can lead to fatigue, creep, or sudden failure.

2) Stress concentrations, such as sharp corners or notches, exacerbate weaknesses.

These elements are interconnected and require comprehensive evaluation to ensure reliability and performance in practical applications. Materials science plays a crucial role in understanding crack propagation as it focuses on the relationships between a material's structure, properties, and performance. Key contributions include:

1) **Fracture Mechanics:** Materials science helps identify how cracks initiate and propagate under various stresses, enhancing safety and reliability in structures.

2) **Microstructural Analysis:** Understanding grain boundaries, defects, and phase distributions provides insights into crack resistance and paths.

3) **Material Properties:** The study of toughness, strength, and fatigue resistance guides the selection and design of materials to prevent catastrophic failures.

4) **Advanced Techniques:** Tools like electron microscopy and computational modeling aid in visualizing and predicting crack behavior at microscopic and atomic scales.

This knowledge is essential for developing materials and designs to mitigate failure in industries like aerospace, construction, and energy.

3. Methodology

3.1. Material Selection

API 5L X70M pipes are widely used in the oil and gas industry due to their excellent mechanical properties and performance under demanding conditions. These pipes are classified under high-strength, low-alloy (HSLA) steel, making them suitable for pipeline applications requiring robust and durable materials (9). Key properties of API 5L X70M pipes include:

- **High Strength:** The minimum yield strength of X70M pipes is 70,000 psi, providing exceptional resistance to deformation under high-pressure conditions.
- **Toughness:** These pipes exhibit excellent toughness, allowing them to perform reliably in extreme temperatures and resist brittle fracture.
- **Weldability:** API 5L X70M pipes are designed for enhanced weldability, ensuring that pipeline sections can be securely joined without compromising structural integrity.
- **Corrosion Resistance:** The material offers good resistance to corrosion, an essential feature for pipelines exposed to harsh environments.
- **Uniform Microstructure:** The controlled microstructure ensures consistent mechanical properties, making it easier to predict performance under stress.

3.2. Sample Preparation

Pipe samples containing transverse cracks were acquired through two primary methods: field failures and controlled laboratory testing.

- 1) **Field Failures:** In-service pipelines that experienced operational failures were

inspected, and segments containing transverse cracks were cut and retrieved (**Figure 1**). These cracks often resulted from fatigue, corrosion, or external mechanical damage. Field samples provide insights into real-world failure mechanisms under varying environmental and operational conditions.



Figure 1. Illustration of a cracked pipeline section retrieved from a field failure.

2) **Laboratory Testing:** Controlled experiments were conducted on pristine pipe segments to simulate transverse cracking. Methods such as cyclic loading, thermal stress application, or notch induction were employed to generate cracks under monitored conditions. These laboratory samples help isolate specific variables influencing crack formation and propagation (**Figure 2**).

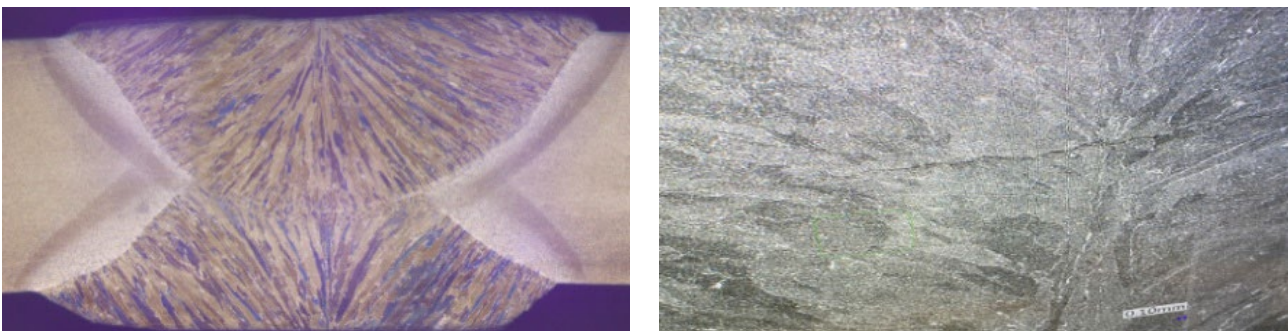


Figure 2. Macro sample of Transverse crack in pipe.

3.3. Testing Techniques

1) Visual Inspection

Visual inspection is the first step in assessing transverse cracks in pipes.

- **External Examination:** The surface of the pipe is inspected for visible cracks, corrosion, discoloration, or deformation. Tools like magnifying lenses, portable microscopes, and borescopes are often used.
- **Internal Inspection:** For internal surfaces, endoscopic cameras or fiberscopes are employed to detect cracks inside the pipe.

2) **Non-Destructive Testing (NDT) Methods:** NDT methods are essential for assessing crack depth, extent, and nature without damaging the pipe (13).

a) Ultrasonic Testing (UT)

- Utilized high-frequency shear waves (by placing the transducer on top of the weld) to detect cracks.
- Utilized an X-pattern to detect defects in an automated Ultrasonic system with a 70-degree shear wave.

b) Radiographic Testing (RT)

Digital Radiography (DR) is a form of X-ray imaging where digital sensors are used instead of traditional photographic film. It provides instant image viewing, enhanced image processing, and easier storage and sharing of results. **Figure 3** shows a digital image of a transverse crack.

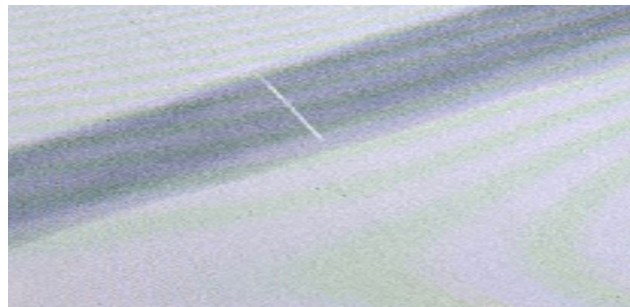


Figure 3. Involves passing X-rays or gamma rays through the pipe and capturing the image on film, Detects internal cracks and voids.

c) Dye Penetrant Testing (DPT)

Dye Penetrant Testing (DPT) is a non-destructive testing (NDT) method used to detect surface-breaking defects in non-porous materials. It involves applying a visible or fluorescent dye to the surface, allowing it to seep into cracks, removing excess dye, and then applying a developer to draw out the dye from defects, making them visible under appropriate lighting. **Figure 4** shows the DPT result for this transverse crack.



Figure 4. A colored or fluorescent dye is applied to the surface, penetrating open cracks. Excess dye is removed, and a developer highlights the cracks.

3) Metallurgical Analysis

Metallurgical analysis investigates the material properties and fracture surfaces to determine the root cause.

a) Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a technique that uses a focused beam of electrons to create high-resolution images of a sample's surface, revealing its texture, composition, and topography at the microscale. **Figure 5** shows the SEM result of the sample.

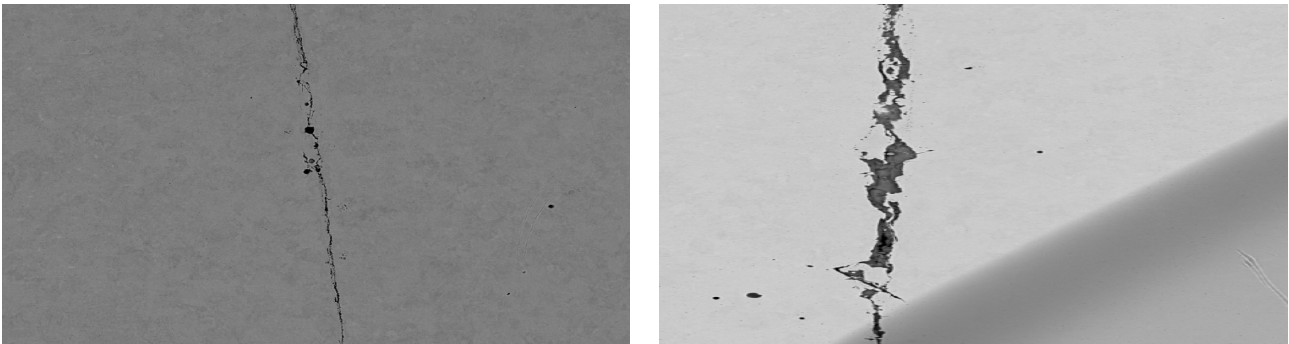


Figure 5. SEM image of crack @ 350X.

b) Optical Microscopy

Figure 6 shows the polished and etched cross-sections to examine microstructures, revealing features like grain boundaries, inclusions, and voids for a sample having a transverse crack.

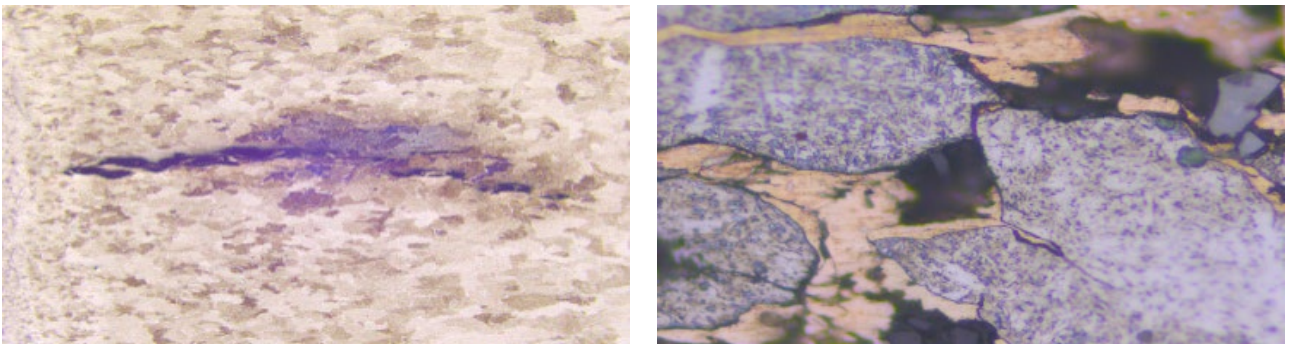


Figure 6. Uses polished and etched cross-sections to examine microstructures, revealing features like grain boundaries, inclusions, and voids.

c) Energy Dispersive X-Ray Spectroscopy (EDS) (10).

4. Results

- The analysis showed distinct crack propagation paths influenced by material heterogeneities, such as inclusions and phase boundaries.
- Surface features near the crack edges showed signs of oxidation and material degradation.
- Elevated concentrations of Mn and O were detected along the crack edges.
- Quantitative analysis revealed Mn content ranging from 32.9 wt% and O content ranging from 33.35 wt%, suggesting the presence of manganese oxides.

- Elemental mapping confirmed that Mn and O were localized predominantly at the crack tips and along the walls.
- **Figure 7** & **Figure 8** show exogenous material in the weld bead that is high in silicon and oxygen together with aluminum, calcium, titanium, manganese, and iron. The chemical makeup together with the location of the inclusion indicates that it is likely slag, flux, and/or oxides.

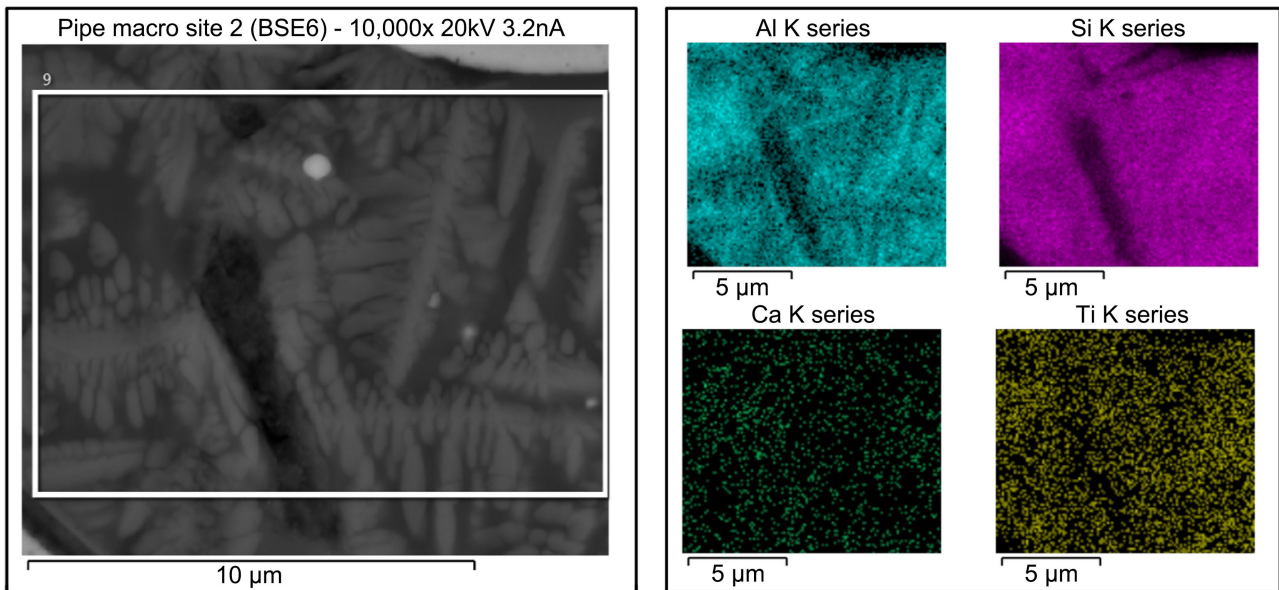


Figure 7. EDS images of crack with surface elements distributions.

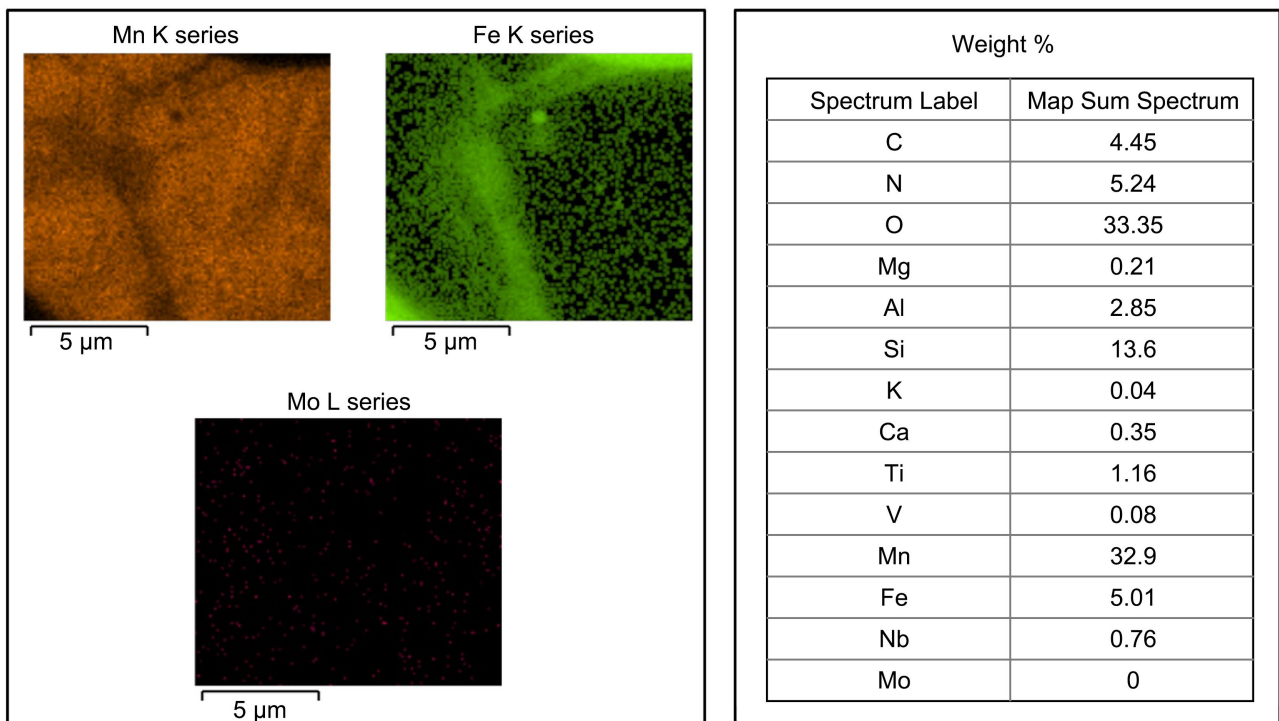


Figure 8. EDS images of crack with surface elements distributions (weight %).

5. Discussion

The mechanical property data, including high yield strength and toughness, suggest that the base material meets API 5L X70M specifications. However, localized hardness increases near crack tips, as observed in microhardness tests, may indicate stress-induced embrittlement, potentially exacerbated by manganese oxides and inclusions. While this study did not quantify fracture toughness or fatigue crack growth rates, the presence of inclusions and oxides likely reduces the material's resistance to crack propagation, supporting the observed failure mechanisms. Future work should include detailed fracture mechanics testing to establish quantitative correlations.

6. Conclusions

- SEM and EDS analyses reveal that manganese oxides play a significant role in crack formation and propagation within the studied sample. These findings underscore the importance of monitoring environmental and compositional factors to mitigate material degradation.
- The examined regions of the exogenous inclusions all contain concentrations of silicon, oxygen, aluminum, calcium, manganese, and iron. All these elements concentrated together indicate that the inclusions are likely a combination of flux, oxides, and/or slag most likely all three.
- As welding flux that has gathered metallic oxides (as is intended) the resultant slag was somehow trapped in the weld rather than floating to the surface. Reference back to **Figure 9** shows that this exogenous material is inside the weld bead of the first weld pass on the inside of the pipe. Entrapped slag or oxides are generally due to the technique or operation of the welding machine. The amounts of silicon and oxygen are much too high to have come from the base metal. The location within the weld bead at the parent metal interface reinforces this assertion.

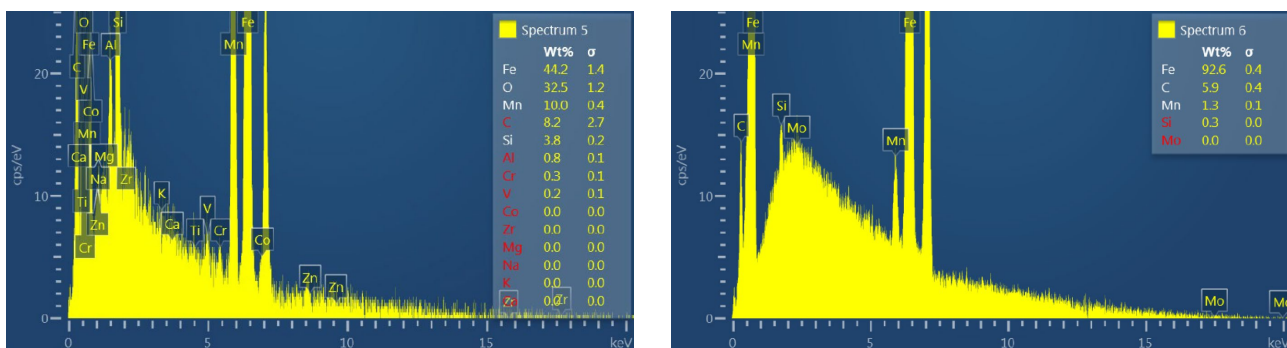


Figure 9. Slag (internal defect) found in crack.

- Given that this study analyzed a limited number of samples, the findings are specific to the conditions tested, as per API 5L 46th edition requirements. To enhance the applicability of these results to a wider range of X70M pipelines,

future research should include larger sample sizes and diverse operational environments.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] American Petroleum Institute (API) (2020) API 5L Specification for Line Pipe. API.
- [2] ASM International (2002) Failure Analysis and Prevention. ASM Handbook, Volume 11.
- [3] Anderson, T.L. (2005) Fracture Mechanics: Fundamentals and Applications. 3rd Edition, CRC Press.
- [4] Hertelé, S., *et al.* (2016) Pipeline Integrity: Crack Assessment Methods. *International Journal of Pressure Vessels and Piping*, **146**, 1-12.
- [5] McEvily, A. and Walter, M. (2002) Metal Failures: Mechanisms, Analysis, Prevention. *Applied Mechanics Reviews*, **55**, B71-B72. <https://doi.org/10.1115/1.1483355>
- [6] Shanmugam, S., Ramiseti, N.K., Misra, R.D.K., Hartmann, J. and Jansto, S.G. (2008) Microstructure and High Strength-Toughness Combination of a New 700MPa Nb-Microalloyed Pipeline Steel. *Materials Science and Engineering: A*, **478**, 26-37. <https://doi.org/10.1016/j.msea.2007.06.003>
- [7] Park, H.J., *et al.* (2014) Stress Corrosion Cracking of Pipeline Steels in Near-Neutral pH Environments. *Corrosion Science*, **80**, 256-266.
- [8] Jones, D.A. (1996) Principles and Prevention of Corrosion. 2nd Edition, Prentice Hall.
- [9] Zhu, L., *et al.* (2015) Hydrogen-Induced Cracking in High-Strength Pipeline Steels. *Journal of Materials Science*, **50**, 6106-6117.
- [10] API Recommended Practice 571 (2011) Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2nd Edition, American Petroleum Institute.